US.6
A32A1

research review

OFFICE of AEROSPACE RESEARCH

OAR: The Research Agency
of The United States Air Force

VOLUME VI NUMBER 2 FEBRUARY 1967

WHISTLING THROUGH OUTER SPACE

MAJOR FRANK H. ZANDER, Directorate of Engineering Sciences, AFOSR

"Whistlers" are lightning-generated, very low-frequency electromagnetic waves which pass through the ionosphere into the outer ionosphere, or magnetosphere, follow very closely the earth's magnetic-field lines to altitudes ranging from 100 kilometers to 10 earth-radii, and re-enter the lower ionosphere in the opposite hemisphere. Whistlers usually are partially reflected upon reaching the ionosphere from above, and thus echo from one hemisphere to the other, via one or more magnetospheric paths, 20 times or more. When detected and amplified, the signal is heard as a whistle, usually descending in tone and lasting about one second. The peculiar frequency-time behavior of whistlers is the result of dispersion produced along the whistler path by the effect of free electrons acting in the presence of the earth's magnetic field.

The originating flash that produces a whistler also radiates an impulsive signal that travels without dispersion between the earth and the lower boundary of the ionosphere. Since this signal, the causative atmospheric, propagates at the speed of light and appears on the spectrographic records along with the resultant whistler, it serves as an indication, accurate to within several milliseconds, of the time of origin of the whistler. Whistlers are detected and recorded both in the hemisphere of their origin and in the opposite hemisphere. In the opposite hemisphere, the causative atmospheric signal, having traveled thousands of miles, is weakly defined, but still indicates accurately the time of whistler origin.

Several aspects of whistler spectrographs are extremely important to researchers. The time delay--that time between the causative atmospheric signal and the leading edge of the whistler signal--is a measure both of the magnetospheric-path electron density and the strength of the earth's magnetic field encountered. The leading edge of the whistler--that tone initially recorded--serves as an indicator of the geomagnetic latitudes at which the whistler entered and exited the magnetosphere. As the magnetosphere is inaccessible by conventional sounding techniques, the whistler has become a powerful tool for investigating various aspects of this enormous region of space.

Professor R. A. Helliwell, Radioscience Laboratory, Stanford University, under AFOSR support since 1956, has extensively investigated and reported whistler phenomena

in order to enhance our understanding of the mechanisms of interaction between waves and particles in the magnetosphere. (1-3) One of many major accomplishments of this research program was the first description, in April 1965, by Angerami and Carpenter of Helliwell's staff, of the detailed variation of electron density near the "knee" (4-5), a region where the electron density drops from relatively high to extremely low values. For the first time, it was realized that the knee involves an extremely abrupt decrease in electron density, and that this decrease is essentially field-aligned at about four earth radii. This implies the existence of a three-dimensional boundary, or "plasmapause," in the magnetosphere, a doughnut-like shell extending around the earth and separating a dense inner region from a tenuous outer region. The presence of such an abrupt three-dimensional boundary came as a total surprise to scientists, since no previous theory had predicted its existence.

Recently, satellite experiments have confirmed the plasmapause. Measurements show that, on the nightside of the equatorial plane, the plasmapause electron density changes by a factor of from 20 to 100 within the relatively short distance of 0.15 earth radii. Further analysis shows that this abrupt profile is normally unchanged for about 18 hours per day, there being a 6-hour period of rapid radial variation and less precise definition.

Recent findings by Helliwell and his staff are as significant as the knee discovery. They involve the use of whistlers to detect magnetospheric motions. No experimental method exists, other than whistlers, for the large-scale mapping of thermal-ionization motions in the magnetosphere. Other methods, applied at high latitudes, are indirect, involving observations of ionospheric

research review
OFFICE OF AEROSPACE RESEARCH

OAR RESEARCH REVIEW is published monthly by the Office of Scientific and Technical Information (RRYC), Hq Office of Aerospace Research, USAF, 1400 Wilson Boulevard, Arlington, Va. 22209. The objective of this publication is to make a positive contribution to the exchange of information concerning Air Force conducted and sponsored research activities.

JACOB SEIDEN
Editor

WHISTLING THROUGH OUTER SPACE
Maj Frank H. Zander 1

AFCRL COVERS NOVEMBER 1966 ECLIPSE
Upper Atmosphere and Space Physics Laboratories, AFCRL 3

RECENT AFCRL SATELLITE LAUNCHING
Aerospace Instrumentation and Upper Atmosphere Physics Laboratories, AFCRL 4

GAS CHROMATOGRAPHY OF PHOSPHOROUS COMPOUNDS
Dr William L. Ruigh 6

NUCLEAR-INDUCED IONOSPHERIC WAVES
Upper Atmosphere Physics Laboratory, AFCRL 6

PHONON GENERATION BY RADIATION PRESSURE
Microwave Physics Laboratory, AFCRL 7

EFFECTS OF PHONON COUPLING IN MIXED CRYSTALS
Drs. D. W. Langer, Y. S. Park and R. N. Euwema 8

BIRDS AND BEES
Meteorology Laboratory, AFCRL 14

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

For sale by the Superintendent of Documents, U.S. Government Printing Office Washington, D.C. 20402 - $2.75 per year domestic, 75 cents additional for foreign mailing, 25 cents per single copy and 15 cents per Annual Index. Back issues will not be furnished.

phenomena and employing a number of assumptions about the connection between ionospheric observations and transport phenomena much higher along the field lines. The whistler technique allows direct measurement of the movement of material in tubes of force. In this sense, it has already provided the first "direct" experimental evidence that the inner magnetosphere approximately corotates with the earth. The recent studies have also shown that, as predicted by theory, there are radial motions of plasma in the outer magnetosphere, driven by large-scale electric fields. A number of measurements of these motions have been made, revealing inward motion of plasma on the nightside of the earth, and outward motion on the dayside. Continuation of these studies should make it possible to establish an important link between the solar wind and processes in the inner magnetosphere. ★

REFERENCES

(1) Helliwell, R.A., Whistlers and Related Low-Frequency Radio-Wave Phenomena, Final Report, U.S. Air Force Contract AF18(603)-126, 1963.

(2) Helliwell, R.A., A Study of Wave-Particle Interactions in the Magnetosphere and a Complementary Study of the Propagation Characteristics of Whistlers and Related Phenomena, Final Report, Grant AF-AFOSR-783-65, prepared for the Air Force Office of Scientific Research, March 1966.

(3) Carpenter, D.L. and R.L. Smith, "Whistler Measurements of Electron Density in the Magnetosphere," Rev. Geophys., Vol. 2, No. 3, pp. 415-441, August 1964.

(4) Angerami, J.J. and D.L. Carpenter, "Electron Density in the Vicinity of the 'Knee' in the Magnetospheric Electron-Density Profile," URSI Meeting, Washington, D.C., April 1965.

(5) Angerami, J.J. and D.L. Carpenter, "Whistler Studies of the Plasmapause in the Magnetosphere -- 2: Electron Density and Total Tube Electron Content near the 'Knee' in Magnetospheric Ionization," J. Geophys. Res., Vol. 71, No. 3, pp. 711-725, February 1, 1966.

AFCRL covers November 1966 Eclipse

UPPER ATMOSPHERE and SPACE PHYSICS LABORATORIES, AFCRL

Rockets, aircraft, a satellite and a diversity of ground observational sites were used by AFCRL scientists to observe the total eclipse of the sun that occurred 12 November 1966 across South America. The AFCRL eclipse program was the most extensive ever mounted by any single research organization.

The eclipse path entered South America, near Lima, Peru, ran southeasterly across South America through Bolivia and Argentina, and exited near Rio Grande in southern Brazil. AFCRL operations took place in Peru, Bolivia and Brazil.

All of the eclipse observations have a bearing on AFCRL's Space Forecasting Program, which is concerned with the prediction of changes in the aerospace environment that are likely to affect Air Force operations. Under this Program, AFCRL scientists are looking for the precursors of solar magnetic storms, solar proton showers, and variations in solar emissions in general which may affect Air Force communications, detection, and surveillance operations, and the earth's giant meteorological machine.

Experiments were carried aboard two aircraft, AFCRL's KC-135, and NASA's Convair 990. The KC-135 experiments, under the direction of Dr. George Gassmann, were used to make airborne measurements of D-region electron-density variations in the absence of UV and visible light during the eclipse. The relation between solar radiation and day airglow was also studied. The KC-135 was based at Rio de Janeiro. Dr. Richard Dunn was aboard NASA's Convair 990 with an experiment to obtain spectra in the chromosphere between 3,000 and 8,800 angstroms. The 990 operated out of Porto Alegre, Brazil.

Three Nike-Hydac rockets were launched from a site near Rio Grande, Brazil, under the direction of James Ulwick. These rockets were instrumented to measure variations of the X-ray flux, Lyman-alpha radiation, and positive-ion species in the D and E regions.

Two experiments were conducted from a site located at Bage, Brazil. Dr. Gary Sales investigated properties of the D region by means of VLF and LF radio reflections and

cosmic-noise absorption. Dr. Sam Silverman used the Bage site to study the diffusion of light through the atmosphere. These data will provide an essential background in making more meaningful interpretations of measurements of dayglow, aurora and the zodiacal light. Similar observations were made from sites at Choclococha, Peru, and Quehua, Bolivia.

From a site at Huachacalla, Bolivia, Dr. Jack Zirker made ground measurements of the coronal spectra in the 3,000-to-8,800-angstrom region similar to those made by Dr. Dunn from NASA's Convair 990. At the same site, Dr. Charles Hyder measured the structure of coronal magnetic fields. He will seek to determine the processes of excitation of the Green line as a function of position in the corona.

Dr. Jacques Becker, from a site in Arequipa, Peru, observed 25-micron limb darkening near the edge of the solar disk. These measurements will provide a more precise knowledge of the temperature structure of the lower chromosphere. Ronald Straka, from a site at Ancon, Peru, studied microwave emissions from active (that is, sunspot) regions on the sun.

An OV3-2 satellite, carrying experiments by four AFCRL scientists, was launched on 28 October 1966 from the Western Test Range. (See article, "Recent AFCRL Satellite Launching," in this same issue.) Although the experiments aboard were not specifically designed for the 12 November 1966 eclipse observations, the launch was scheduled so that the satellite would be in orbit at the time of the eclipse. The satellite observations will provide data on charged-particle variations in the extreme upper atmosphere before, during, and after the eclipse. ★

RECENT AFCRL SATELLITE LAUNCHING

AEROSPACE INSTRUMENTATION and UPPER ATMOSPHERE PHYSICS LABORATORIES, AFCRL

AFCRL launched an OV3-2 satellite, solely instrumented by AFCRL scientists, on 28 October 1966 from the Western Test Range to measure charged-particle composition, energy, density, temperature, and ion-production rates at altitudes up to 800 nautical miles. This satellite should have an operational lifetime of about one year. Although the experiments aboard the OV3-2 (OV for orbiting vehicle) were not specifically designed for the 12 November 1966 eclipse across South America (which was observed by AFCRL scientists), the satellite provides a rare opportunity for observing eclipse-induced charged-particle variations. (See article, "AFCRL Covers November 1966 Eclipse," in this same issue.)

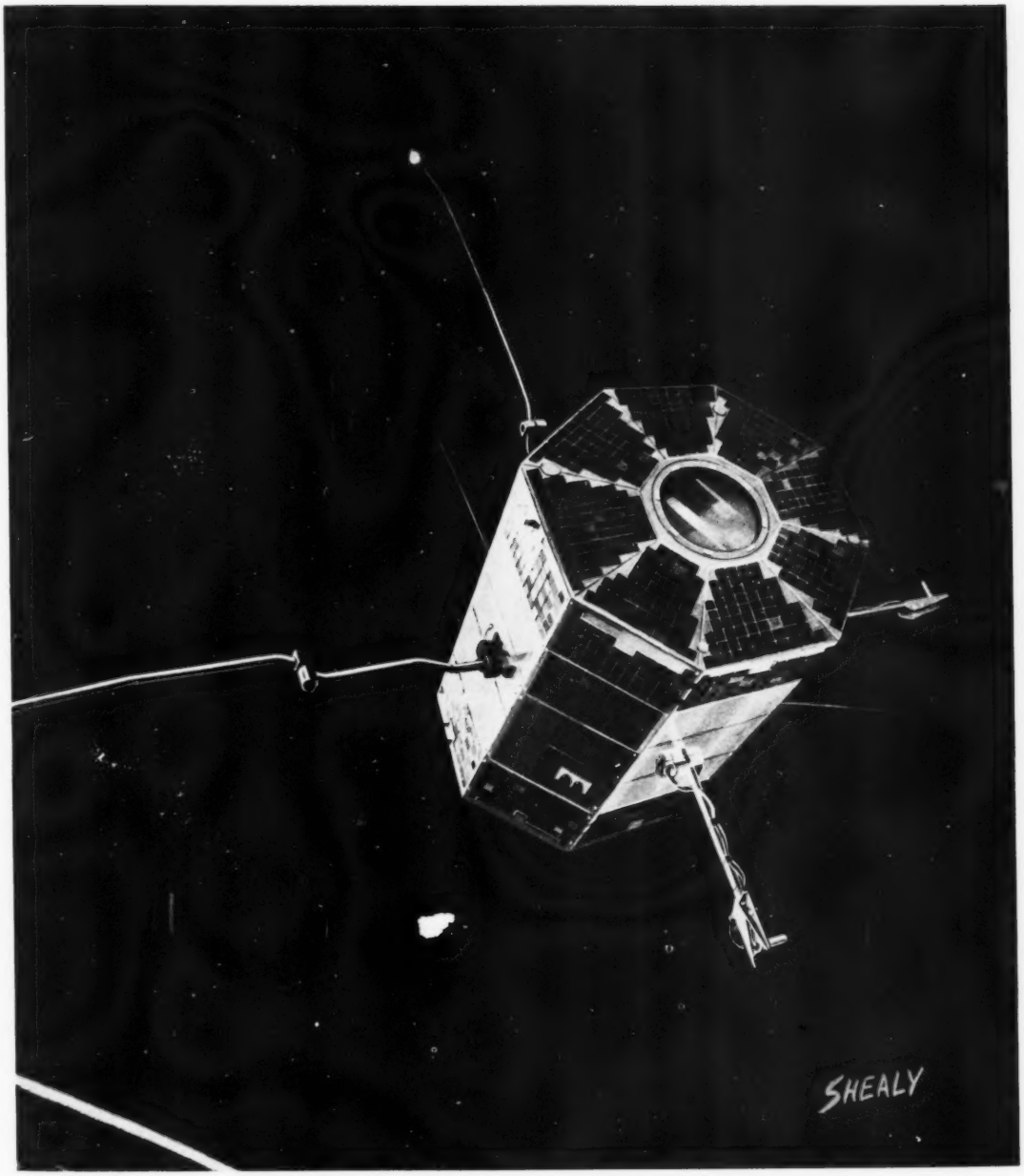
The octagonal-shaped, 200-pound satellite has an orbital inclination of 82 degrees, an apogee of 800 nautical miles, and a 180-nautical-mile perigee. A solar sensing system and three magnetometers give three-aspect information for determining the spacecraft's spin rate, its precession rate, and the angle between the spacecraft's spin axis and the sun. Five types of instrumentation are measuring different aspects of charged particles in near space, as follows:

(1) Two electrostatic analyzers are being used for measuring the angular distribution of electrons. Each sensor, separated by 180 degrees, measures the energy spectra and angular distribution of electrons in the 15-to-80-kev-energy range.

(2) A quadrupole ion mass spectrometer is being used to measure positive-ion composition in the upper atmosphere. Spectrometer data, used in conjunction with data from other experiments on the spacecraft, will yield data (ions per cubic centimeter) for each constituent of the atmosphere.

(3) Two spherical plasma probes, situated on booms extended 54 inches from the spacecraft, are being used for measurements of the spatial and temporal variation in the concentrations and energy distribution of charged particles in the energy range of 0 to 2 kev.

(4) Retarding potential analyzers are being used to measure electron density and tem-



perature. The two sensors are mounted at the end of another 54-inch boom.

(5) Standing-wave impedance probes are also being used to measure electron density. The apparatus consists of two 30-foot extendable dipoles, an artificial transmission line, and electronics to generate 2 and 7.2 MHz frequencies.

The AFCRL experiments were designed by James C. Ulwick, Herbert A. Cohen, Rita C. Sagalyn and John A. Sandock. Charles Reynolds is the Manager for the satellite program. Joseph F. Geary, Jr., is the pay-load Manager. ★

GAS CHROMATOGRAPHY OF PHOSPHOROUS COMPOUNDS

DR. WILLIAM L. RUIGH, Directorate of Chemical Sciences, AFOSR

Chromatography is the technique of separating or detecting chemical substances by flowing a gas or liquid over a stationary material on which may be suspended or adsorbed another material. There are a number of different kinds of chromatography, such as liquid, ion-exchange, "thin-layer," paper, and gas chromatography.

The first published work in this area was that of Tswett (1905-1910), who separated various dyes and colored materials, such as plant pigments. The name, chromatography, shows the origin of the term. In later work, colorless substances were also separated by the chromatographic technique. The method was not used generally until the publications of Martin and Synge, in 1941. The exploitation of this technique was explosive, and now new journals and books dealing solely with the subject have appeared. When the flowing phase is a gas or vapor instead of a liquid, the technique is known as gas chromatography. A recent book covering this method was written by J. H. Knox, and is entitled, Gas Chromatography.

The theory of chromatography is related to the well-known HETP (height-equivalent-to-a-theoretical-plate) formulas originally developed for separations by distillation. However, in actual use, gas chromatography is more of an empirical art than a true science. The choice of a carrier gas, substrate, temperature of column, the choice of the detector, and many other factors play a significant role in the development of a specific system to separate a mixture.

In the course of his work on "Nucleophilic Displacements on Trivalent Phosphorus," Dr. K. Darrel Berlin of the University of Oklahoma, under AFOSR sponsorship, has developed several new systems for the analysis of phosphorous compounds. As the result of this work, Dr. Berlin recently published a paper entitled, "Gas Chromatographic Analyses of Organophosphorous Compounds Using a Hydrogen Flame Ionization Detector." The column used most by Dr. Berlin was a length of 1/8-inch stainless-steel tubing 6 feet long. The packing was 5% silicone-30 on chromosorb-G, which had previously been "silanized" as follows: chromosorb-G (60/80 mesh) was first acid-washed and then treated with dimethyldichlorosilane. The temperature of the column was between 200 and 300 degrees centigrade. Using such a column, Dr. Berlin was able to separate mixtures of phosphorous compounds such as phosphine oxides, phosphine sulfides, phosphinates, phosphonates, phosphates, phosphine acids, phosphorylated amidines, phosphines, and phosphites.

This research by Dr. Berlin is of importance in the separation and detection of minute amounts of various phosphorous compounds. The work may also be useful in the design and development of detectors for toxic gases, including phosphorous fluorine compounds. ★

nuclear-induced ionospheric waves

UPPER ATMOSPHERE PHYSICS LABORATORY, AFCRL

A high-altitude nuclear explosion sets up a train of wave-like undulations in the ionosphere that encircle the world. During the 1962 series of atomic tests in the Pacific, 54 world-wide ionosonde observation sites were used to measure the velocity of these nuclear-induced ionospheric waves, their amplitude, and their length. Dr. George Gassmann of AFCRL has recently reported on the results of these measurements.

Ionospheric physicists have known for many years that the upper ionosphere, like the oceans, is in a state of constant agitation. This is most pronounced in the highest layer of the ionosphere, the F2 layer, at about 400 km. We see evidence of this undulation in the variations in phase and amplitude of radio

signals from space that have passed through the atmosphere.

Five high-altitude nuclear detonations of the 1962 Fishbowl series of tests, all launched from Johnston Island, were observed at the 54 sites. The effects of these detonations were observed as changes in the F2-layer critical frequency, which is the limiting frequency below which the signal transmitted by the ionosonde is reflected by, and above which it penetrates through, an ionospheric layer at vertical incidence. The critical frequency, in turn, varies with variations in electron density. Thus, the ionosonde stations derived information on the nuclear-induced waves by measuring the time needed for an electron-enriched region of the ionosphere to travel from one station to another.

The effect of a nuclear explosion in the ionosphere might be compared to that of a rock dropped into a pool of water--except that the resultant wave motions in the ionosphere are much more complex. Instead of a single wave radiating outward radially from a source, a series of waves traveling at different velocities are set in motion. The various wave trains have velocities ranging from 50 to 900 meters a second (roughly 112 to 2,000 miles an hour).

The several wave structures observed have been interpreted as a degeneration of the initial nuclear-induced shock wave. With this degeneration, several waves, each traveling at different velocities, are formed. For this reason, a particular wave front often seems to start from a point some distance from the Johnston Island launch point. A further difficulty in measuring the wave front comes about because of the differences in electron density on the sunlit and shadowed sides of the earth: the ionosphere waves, therefore, do not travel in a uniform medium.

Because the ionospheric wave, as observed by ionosondes, constitutes undulations of charged-particle density, it might be expected that the dispersion of the wave front would show some preferential alignment with the earth's magnetic field. No such correlation in this respect, however, has been found. This fact suggests that the ionospheric waves, although easily observable, are actually a mere side effect of wave motions involving neutral particles. Theory indicates--although this is difficult to verify from measurements--that the actual waves are not dominated by plasma motions but by gravity and compression.

Prior to the analysis of the ionospheric disturbances from the five U.S. high-altitude nuclear detonations in 1962, the most complete previous analysis of traveling ionospheric waves was done on the basis of the disturbance brought about by the Russian nuclear detonation at Novaya Zemlya on 30 October 1961. ★

PHONON GENERATION BY RADIATION PRESSURE

MICROWAVE PHYSICS LABORATORY, AFCRL

Pressure on a material, however slight, imparts some strain to the material. Strain is another way of saying that we have displaced atoms in the material. In doing so, we have generated phonons.

Radiation pressure as well as mechanical pressure can achieve this. In fact, the first experimental measurement of the true static radiation pressure of light was carried out in 1899. When the radiation is coherent, we not only have the more familiar static pressure, but second harmonic phonons as well.

In experiments conducted by Dr. Paul H. Carr of AFCRL, the second harmonic variation of the radiation stress has been observed for the first time. Phonons have been generated in both ruby and in nonpiezoelectric quartz rods. In the experiments, one end of a rod is placed in a 4.5-GHz resonant cavity, and the other end is placed in a 9-GHz cavity. When electromagnetic energy is introduced into the 4.5-GHz cavity, the radiation pressure generates 9-GHz sound waves at the end surface of the rod. The sound waves, or

microwave phonons, propagate to the other end of the rod in the 9-GHz cavity. On this end of the rod is deposited a thin-film piezoelectric cadmium-sulphide transducer, used to convert the 9-GHz ultrasonic wave into 9-GHz electromagnetic energy.

Only a minute fraction of the input energy is recovered, and the efficiency of generation is much less than that of the more familiar piezoelectric effect at the maximum electric field (10^5 v/cm) achieved. However, since the piezoelectric strain is proportional to the electric field, and the radiation strain to the square of the electric field, the radiation stress could be larger than the piezoelectric stress if much larger fields could be achieved. Radiation pressure has an additional advantage in that it can produce phonons in any material--not only in piezoelectric materials, of which there are relatively few.

To detect the microwave phonons (which have wave lengths of about 5,000 angstroms) with a cadmium-sulphide transducer, fabrication of the rod requires great precision. The crystalline lattice of the rod was oriented with optical and X-ray techniques to within one half degree of arc before fabrication of the ends, which were optically flat and parallel to an accuracy of one tenth of a wave length of sodium light.

Because the generation of phonons in the material represents nothing more than inducing a strain along the end surface of the material, Dr. Carr's efforts have consisted largely of a theoretical study of the physical processes producing the strain. Agreement between the predicted and measured values of the strain amplitude have verified that radiation pressure is the physical process generating the phonons. ★

EFFECTS OF PHONON COUPLING IN MIXED CRYSTALS*

DRS. D. W. LANGER, Y. S. PARK, and R. N. EUWEMA, Solid State Physics Research Laboratory, ARL

Recently, using electron-beam stimulation, C. E. Hurwitz obtained laser emission from CdS and CdSe single-crystal platelets. He also demonstrated that mixtures of Cd(SeS) show laser emission at wave lengths which depend on the Se:S ratio of the mixture, (1) and lie between the values of the pure compounds, 2.55 and 1.83 eV. Hurwitz noted that the threshold value for laser action was lower in CdSe than in CdS, and that the threshold of many mixtures was still lower than that for CdSe. The latter was a surprise to those of us in this Laboratory who have been working with this class of crystals for a long time, and who have grown the very crystals used by Hurwitz in the above experiments. We have considered the Cd(SeS) mixtures to be less perfect in crystal structure than either the pure CdS or the pure CdSe crystals. Therefore, the lifetime of the excited state, in which population inversion has to be achieved for stimulated emission, if effected at all, should be shorter. Hence, on first thought, the threshold for laser action in the mixtures should not be smaller than the one for CdSe.

These considerations did not take into account, however, the effects of phonon coupling in mixed crystals which we subsequently investigated and report as follows: given a sufficiently large number of electrons in the conduction band by initial pumping, the rate of population of the excited level from which stimulated emission may occur is affected by the rate of energy loss of the conduction electrons through emission of longitudinal optical (LO) phonons. This fact, and the spectrum of these phonons, can explain the lower threshold for laser action of mixtures. These results, demonstrated for Cd(SeS)-mixed crystals, point out a feature which should be valid in general, also, for other mixed-crystal systems.

Through the study of the edge-emission spectrum, described in the next section, we gained a detailed knowledge of the LO phonons present in Cd(SeS) mixtures. Through the study of the photoconductivity described in section II below, we convinced ourselves

Complete treatment appeared in the Phys. Rev., Dec. 9, 1966 issue.

that electrons from the conduction band populate a recombination level by the emission of LO phonons. In mixtures there are essentially two LO phonons with different energies which cause an increased rate of population of the recombination level, thus a lower threshold for laser emission.

I. Phonon Coupling to Edge Emission

The edge emission of II-VI compounds below 4°K consists of broad bands due to donor-acceptor recombinations as well as lines due to the annihilation of free excitons,

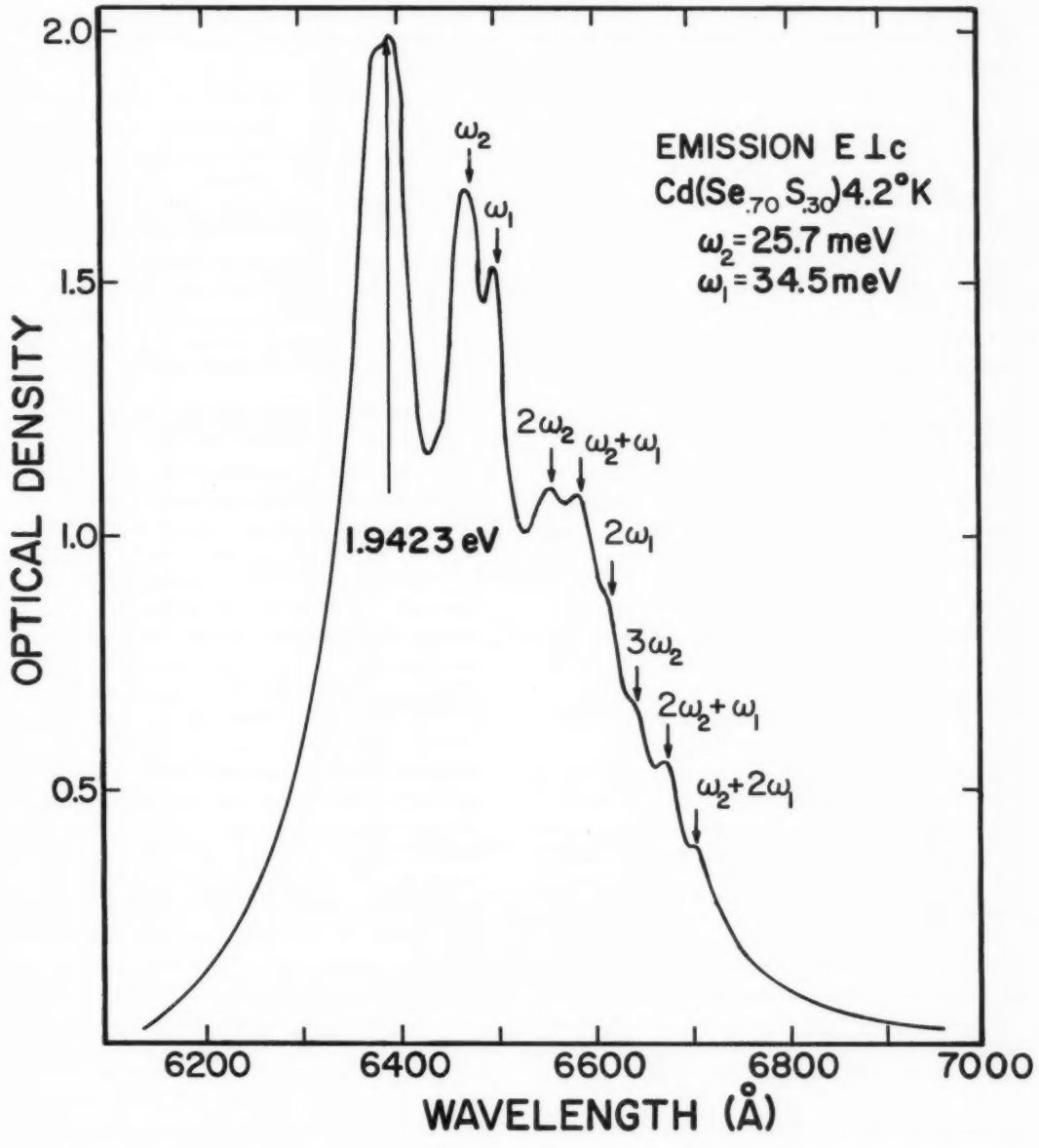


Fig. 1. Edge emission of a mixed CdSe-CdS crystal. The structure may be explained in terms of phonon emission (two different LO phonon frequencies [ω_1 and ω_2] and their additive combinations).

or excitons bound to impurities, which were subject to many detailed studies in this Laboratory. (2) These spectra show a characteristic periodic structure, the period of which corresponds to the energy of the longitudinal optical (LO) phonons in the respective lattices. For CdS, by precisely measuring the separation of the I_1 line (4888.5Å) and its first phonon satellite, we determined that an accurate value of the LO phonon in CdS is $\omega_1^0 = 37.7 \pm 0.1$ millielectronvolts (meV). Similarly, we determined the LO phonon energy of CdSe to be $\omega_2^0 = 26.6 \pm 0.3$ meV.

Figure 1 shows the edge emission of a typical sample $Cd(Se_{.70}S_{.30})$. The structure is analyzed, assuming that energy increments consisting of additive combinations of two values, ω_1 and ω_2, couple to the parent transition, the line of 1.9423 eV. In this and other measurements the energy values of ω_1 are always found to be smaller (and increasingly smaller for higher Se concentration) than the LO phonon energy in pure CdS. Similarly, ω_2 is also smaller (and increasingly smaller with higher S concentration) than the LO phonon energy in pure CdSe.

The data seem to suggest that, in solid solutions, there may exist two different LO phonons and their additive combinations, all of which couple to the recombination radiation.

Unfortunately, the computation of vibrational frequencies in a three-, or even in a two-dimensional, lattice of Cd(SeS) in a Wurtzite structure is very difficult; moreover, such calculations are usually so restrictive that they do not lend meaningful support to a physical model of the measured frequencies.

We, therefore, calculated the eigenfrequencies and the respective oscillator strengths of a linear-chain model of CdSeCdSCdSe. . . . . For each composition we chose the most probable arrangement of CdSe and CdS molecules within a 12-molecule cell.

The results of these computations are presented by the peaks in Figure 2. Each chain, of course, has 24 eigenfrequencies. The oscillator strengths of most of them are, however, many orders of magnitude lower than those depicted. The heights of the peaks in Figure 2 correspond to the logarithm of the calculated oscillator strengths. Clearly, one distinguishes two branches, ω_1 and ω_2. The center of gravity of these branches as a function of the composition are shown as heavy solid lines. The experimentally determined values are shown by squares and circles.

The over-all agreement of the observations with the predictions of this model affirms our initial assumptions--namely, that the Cd(SeS) crystals actually form a solid solution, and that the observed emission side bands are results of phonon emission in the mixed crystals. Further, we are led to the conclusion that in these mixed crystals, in contrast to pure crystals, two different LO phonon modes and their additive combinations can be emitted into the lattice.

II. Phonon Coupling to Free Electrons

Periodic structure in the spectral dependence of photoconductivity (PC) has been observed previously in CdS. (3) This phenomenon is illustrated in curve (a) of Figure 3. The peaks at the near-zero are due to excitons. Toward higher energy, the minima marked by arrows are separated by equal energy differences which correspond approximately to ω_1, the energy of the LO phonon in CdS. The first minimum is displaced also by ω_1 from the A_1 exciton peak. These minima are due to the fact that the lifetime of the conduction electron at certain energy values is smaller than that at adjacent energy values, namely, at those energy values which coincide with the sum of the energies of an exciton plus a multiple of the LO phonon energy. Figure 4 shows a simplified model of the band structure applicable to CdS, CdSe and Cd(SeS) crystals with Wurtzite structure. The right-hand side of Fig. 4 might be considered to represent the curve (a) in Fig. 3. The positions of the transitions (indicated by vertical arrows, pointing upward) are chosen such that their corresponding energies are equal to the sum of an A-exciton plus a multiple of LO phonons, i. e., they are equal to the energies at which minima were observed. From these points

in the conduction band, transitions to the exciton level might easily occur via LO phonon emission. The exciton usually decays radiatively.

In CdSe, we observe essentially the same phenomena as in CdS. Curve (c) in Fig. 3 shows the PC response curve. The A-exciton peak is at zero on the energy scale. The

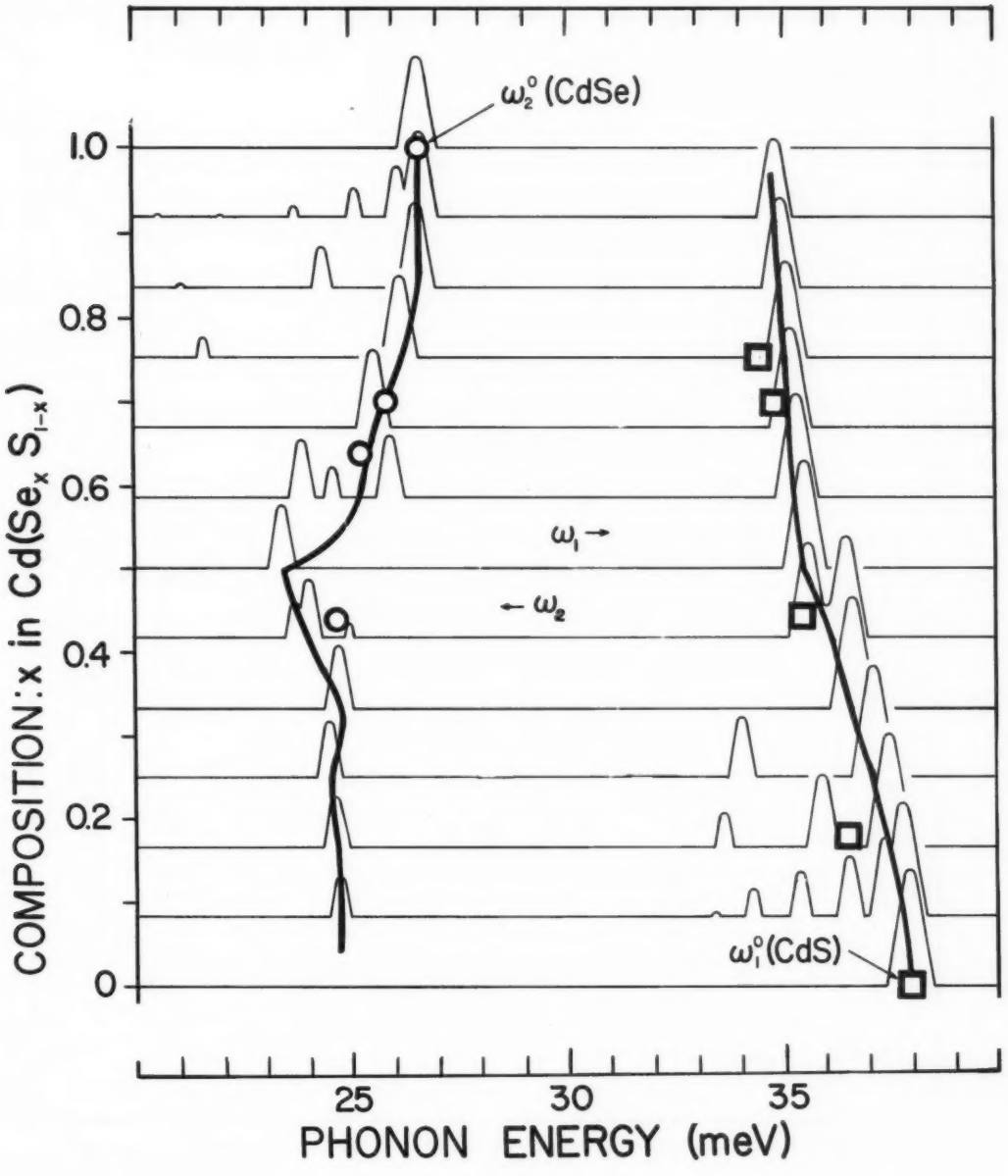


Fig. 2. The computed LO eigenfrequencies of a mixed CdSe-CdS chain. The heights of the peaks represent the oscillator strength. The heavy lines are drawn along the center of gravity of the ω_1 and ω_2 branches, and should be compared with the experimentally obtained points (squares and circles, respectively).

minima indicated by the long arrows are separated by ω_2, the LO phonon energy of CdSe. Various other series of minima are also observed in different crystals as, e.g., the one indicated by short arrows in curve (c). They show the same characteristic spacing, ω_2, between minima and are due to transitions of conduction electrons to an

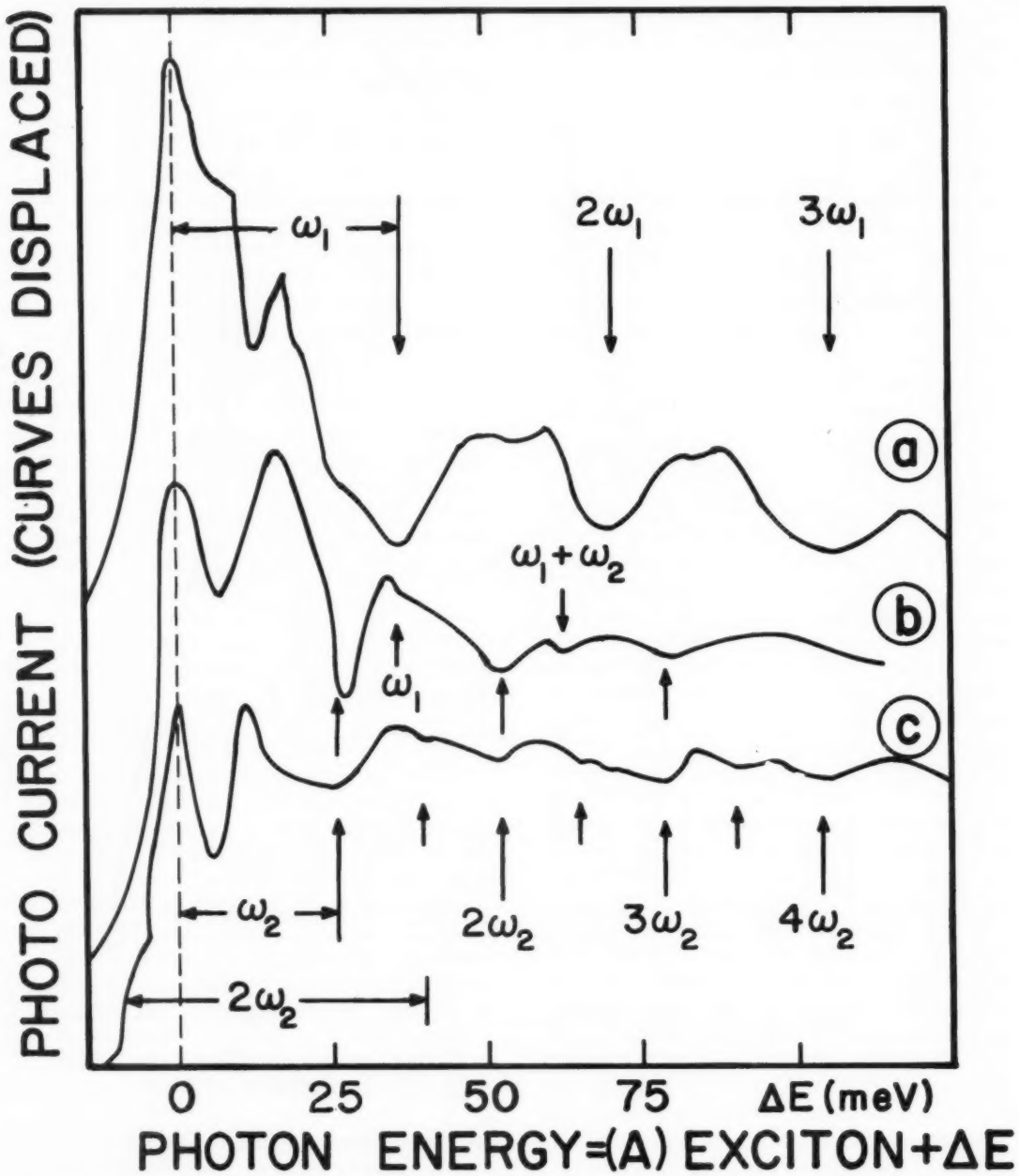


Fig. 3. Photocurrent vs. energy of: (a) CdS; (b) $Cd(Se_{.64}S_{.36})$; and (c) CdSe. Zero of the energy scale is the position of the respective A-exciton: 2.554, 1.959 and 1.826 eV.

impurity complex, and not to the free exciton, via emission of LO phonons.

The PC response in mixtures of Cd(SeS) is shown in curve (b) of Fig. 3. Minima can

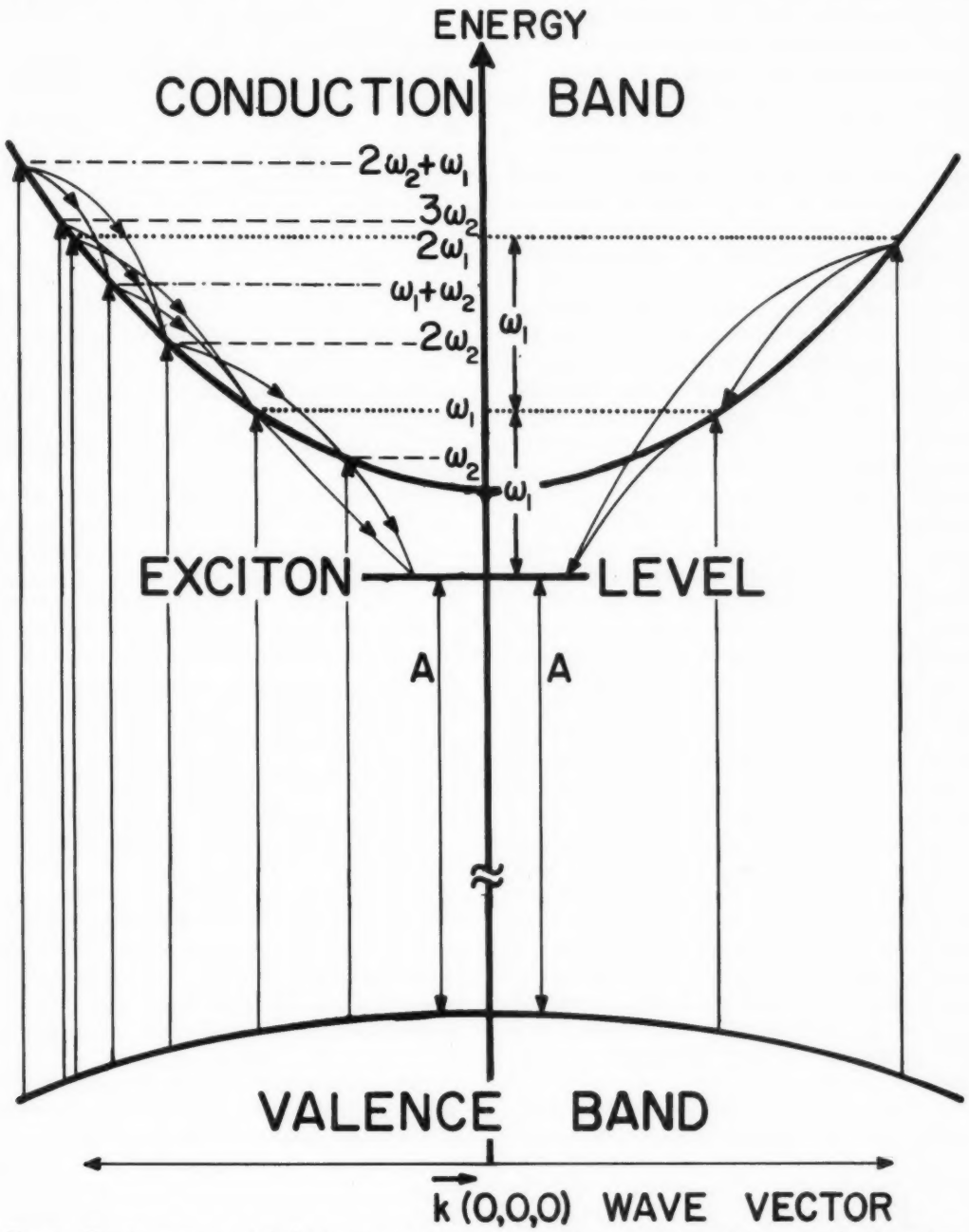


Fig. 4. Band structure of CdS-like crystals, illustrating the excitation and the cascade of conduction electrons to the recombination center via LO phonon emission: in pure crystals (right side), and in mixed crystals (left side).

be identified which are separated from the A exciton peak by energies which correspond roughly to the energies ω_1 and ω_2 (the LO phonons in CdS and CdSe), and to the three additive values obtainable from the two phonon energies $2\omega_1$, $\omega_1+\omega_2$ and $2\omega_2$.

Seen in conjunction with the previous edge-emission spectra, these observations lead to the conclusion that, in $Cd(Se_xS_{1-x})$ mixtures, coupling to 2 different LO optical phonons, ω_1 and ω_2, and also to their additive combinations, gives rise to energy levels which are distinguished by a high transition probability. As in pure crystals, the emission of LO phonons to the lattice permits the electrons to cascade faster to the energy level of the exciton than would be possible by the emission of acoustical phonons only. In comparison with the pure crystal, however, it is evident that, with the possibility of cascading via the emission of the 2 different LO phonons, electrons from a larger number of energy levels will have ways of cascading fast toward the exciton level. The left-hand side of Figure 4 shows this process schematically in contrast to the case of the pure crystal, as shown on the right-hand side. At energies between 0.1 and 0.2 eV above the bottom of the conduction band, e.g., there exist 3 levels in CdS--and 4 in CdSe--from which electrons may cascade fast to the recombination level. In the mixed crystal, however, 23 such levels exist in the same energy interval.

The fact that electrons in a given energy region of the conduction band cascade to a recombination center from an increased number of levels in the mixed crystals means that, after a polychromatic excitation, more electrons will cascade in a given time; hence, the population density of the recombination center will be increased, accounting for a lower threshold for laser emission. ★

REFERENCES

(1) Hurwitz, C.E., Appl. Phys. Letters, 8, 121, 243, 1966.

(2) Reynolds, D.C., C.W. Litton and T.C. Collins, Phys. Stat. Sol., 9, 645, 1965 and 12, 3, 1965.

(3) Park, Y.S. and D.W. Langer, Phys. Rev. Letters, 13, 392, 1964.

BIRDS AND BEES

METEOROLOGY LABORATORY, AFCRL

Angels, or mysterious echoes from a clear sky, have cluttered up radarscopes ever since the beginning of radar, confusing the operator's attempts to keep targets of operational interest separated from spurious ones.

One class of these spurious targets--known as "dot angels"--has been attributed to three sources: birds, insects, and atmospheric refractivity perturbations. A previously unresolved question is just how much each contributes to the dot-angel problem.

In experiments conducted by Dr. Kenneth R. Hardy, Kenneth M. Glover, and Claude R. Landry of AFCRL, and by Thomas G. Konrad of Johns Hopkins' Applied Physics Laboratory, it has been found that, for the most commonly observed dot angels, insects are the sole contributors--not swarms of insects, but single individual specimens. Those assisting in the experiments have included W. N. Sullivan and A. S. Michaels, entomologists of the Department of Agriculture. The studies are being conducted at the Wallops Island radar site in Virginia. At this site are located 3 high-power, high-intensity radars operating at different wave lengths: 3.2, 10.7, and 71.5 cm.

The experiments are fairly straightforward. In a typical experiment, a honeybee is fed sugar water (for energy) and is taken to an altitude of about 5,000 feet in a small single-engine aircraft and dropped overboard. One or more of 3 radars, about 7 miles away and pointed toward the drop zone, pick up the small target. The horizontal and vertical flight paths of the insect are plotted.

Analysis shows differing kinds of radar returns from different insects. The flight of the hawk moth, for example, results in two kinds of fluctuations. The wing beat causes a large amplitude fluctuation. A less distinct oscillation pattern occurs when the insect is tumbling in free fall.

In addition to the hawk moth, the honeybee, the tobacco budworm, and the dragonfly were tested. Release altitudes varied from 5,000 to 10,000 feet. Of the insects tested, the honeybee proved to be of greatest interest. It is a strong flyer capable of maintaining a velocity of more than 20 feet a second relative to the wind for exceptionally long periods of time. (To assure good health and a vigorous flight by the insects, the Department of Agriculture entomologists provided for special care and feeding of the test insects.)

Similar studies were conducted with birds--pigeons, grackles and sparrows. Birds are easily identified as birds on a radarscope. There is a strong wave-length dependence--that is, radar reflections from birds are most pronounced at 10 cm. Over the years, radar cross sections of birds have been extensively measured, and there is a large body of cross-section data to draw on. As early as 1950, for example, AFCRL made radar cross-section measurements of ducks, such data being important to the designers of large arctic radars for the then-projected air-defense network. Because birds can be readily identified, the problem is narrowed to the question of the relative contributions of insects and of refractivity surfaces to the dot-angel phenomenon.

The long wave length relative to specimen size precludes the detection of insects by radars operating at wave lengths of 71.5 cm or greater. The problem is thus further narrowed to the examination of dot angels observed at shorter wave lengths.

In measuring the radar cross section of insects at 3.2 and 10.7 cm, the AFCRL experimenters found a strong wave-length dependence, this ranging from the inverse first to the inverse third power of the wave length. It was this wave-length dependence that removed the ambiguity between angels caused by insects and those caused by refractivity structures. In a separate analysis by AFCRL, it was shown that no conceivable atmospheric structure could be the source of dot angels if the wave-length dependence was less than the inverse second wave length. Thus, for one major class of dot angels, all are caused by single insects in free flight.

The AFCRL scientists are interested in resolving a particular type of radar problem--namely, that of dot angels. The interests of the two Department of Agriculture entomologists assisting in the program are, however, in another direction. In these studies, they see the potential of an important new research tool which will permit entomologists to obtain information on insect behavior heretofore unobtainable. The studies show that, with radar, it is possible to track flying insects at relatively great distances, and to observe their flight patterns and migrations. ★

PROFILES

The AFCRL team of Dr. Kenneth R. Hardy and Messrs. Kenneth M. Glover and Claude R. Landry has been conducting experiments on the relationship of single free-flying birds and insects to radar "dot angels." Their conclusions are summarized in the article, "Birds and Bees," appearing in this issue of the Review. Dr. Hardy is Acting Chief of the Weather Radar Branch, Meteorology Laboratory. He is currently investigating the structure of the atmosphere, using radar measurements in clouds and in clear air. Dr. Hardy received his B.A. with Honors in Physics (1952) from the University of Saskatchewan, his M.A. in Meteorology (1953) from the University of Toronto, and his Ph.D. in Meteorology (1963) from the University of Michigan. Before joining AFCRL, he served with the Canadian Meteorological Service and the Weather Engineering Corporation of Canada. Mr. Glover, a physicist with the Weather Radar Branch, received both his A.B. in Mathematics (1958) and his M.S. in Physics (1960) from Miami University, Oxford, Ohio. He has been with AFCRL since 1962, doing research on back-scattering by both simulated and real meteorological targets. Mr. Landry, a physical science technician with the Weather Radar Branch since 1960, took various courses in meteorology while on military duty with the Air Force. He did typhoon reconnaissance in the Pacific for the Air Weather Service from 1956 to 1958.

Dr. George J. Gassmann, whose work is discussed in "Nuclear-Induced Ionospheric Waves" in this issue of the Review, is a supervisory research physicist with the Ionospheric Radio Physics Branch, Upper Atmosphere Physics Laboratory, AFCRL. He has been with AFCRL and its predecessor, AFCRC, since 1952, engaged in the development of equipment and techniques for airborne measurements pertaining to the ionosphere and Van Allen belts, atmospheric tidal motions, ionospheric drifts, solar-eclipse effects, and nuclear effects on communications and radar. Dr. Gassmann studied at the Universities of Würzburg, Vienna, Munich, and Göttingen, and in 1939 received his Dr. Natural Sciences. In Germany, before coming to the United States, he was concerned with radio navigation systems, medical X rays, and other applied fields. He is a member of the American Geophysical Union and was appointed by the National Academy of Sciences to Commission III of the International Scientific Radio Union.

Dr. Paul H. Carr is a solid-state physicist with the Microwave Physics Laboratory, AFCRL, engaged in research on the generation of microwave phonons and on their interaction with each other (phonon-phonon scattering) and with magnetic materials. He received both his B.S. in Physics (1957) and M.S. in Physics (1961) from M.I.T., and his Ph.D. in Physics (1966) from Brandeis University. He has done research at the Lincoln Laboratory on the galvomagnetic effects in semiconductors and in magnetic transition in Ti_2O_3 and V_2O_3. On active duty as an officer at the Army Missile Command Calibration Center, he worked on a new technique for the calibration of accelerometers, infrared and optical detectors, and vacuum gauges. Dr. Carr is a member of the American Physical Society and Sigma Xi. He has about 10 research papers to his credit. "Phonon Generation by Radiation Pressure," in this issue of the Review, describes some of Dr. Carr's recent work.

TO OUR READERS

Request for further information should be directed to the individual or laboratory of origin (except for those from Latin America).

Addresses are as follows:

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
Attn: CRI
Laurence G. Hanscom Field, Bedford, Massachusetts 01731

AEROSPACE RESEARCH LABORATORIES
Attn: ARI
Wright–Patterson Air Force Base, Ohio 45433

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Attn: SRGL
1400 Wilson Blvd, Arlington, Va. 22209

THE FRANK J. SEILER RESEARCH LABORATORY
USAF Academy, Colorado 80840

OFFICE OF RESEARCH ANALYSES
Attn: ORR
Holloman AF Base, New Mexico 88330

Request for further information from institutions and individuals in Latin America should be addressed to:

LATIN AMERICAN OFFICE OF AEROSPACE RESEARCH
U. S. EMBASSY
Rio de Janeiro, Brazil

Detailed documentary reports may be obtained from:

CLEARINGHOUSE
U. S. Department of Commerce, Springfield, Virginia 22151

DEFENSE DOCUMENTATION CENTER FOR SCIENTIFIC AND TECHNICAL INFORMATION*
Cameron Station, Alexandria, Virginia 22314

* Qualified requestors

GPO 919-185